Environmental Science & Technology

Article

pubs.acs.org/est

How Well Do We Know the Future of CO_2 Emissions? Projecting Fleet Emissions from Light Duty Vehicle Technology Drivers

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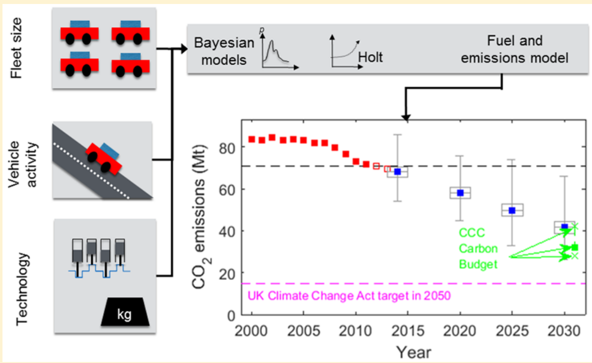
Supporting Information

ABSTRACT: While the UK has committed to reduce CO_2 emissions to 80% of 1990 levels by 2050, transport accounts for nearly a fourth of all emissions and the degree to which decarbonization can occur is highly uncertain. We present a new methodology using vehicle and powertrain parameters within a Bayesian framework to determine the impact of engineering vehicle improvements on fuel consumption and CO_2 emissions. Our results show how design changes in vehicle parameters (e.g., mass, engine size, and compression ratio) result in fuel consumption improvements from a fleet-wide mean of 5.6 L/100 km in 2014 to 3.0 L/100 km by 2030. The change in vehicle efficiency coupled with increases in vehicle numbers and fleet-wide activity result in a total fleet-wide reduction of 41 ± 10% in 2030, relative to 2012. Concerted internal combustion engine improvements result in a 48 ± 10% reduction of CO_2 emissions, while efforts to increase the number of diesel vehicles within the fleet had little additional effect. Increasing plug-in and all-electric vehicles reduced CO_2 emissions by less (42 ± 10% reduction) than concerted internal combustion engines improvements. However, if the grid decarbonizes, electric vehicles reduce emissions by 45 ± 9% with further reduction potential to 2050.



INTRODUCTION

UK passenger vehicles accounted for 18%[1] and 13%[2] of national primary energy consumption and carbon dioxide (CO_2) emissions, respectively, in 2014. The UK is committed to an 80% reduction in CO_2 equivalent emissions (CO_{2e}) by 2050, relative to 1990 values (780 $MtCO_{2e}$[3]), which is in line with those made at the European level. This has forced policy makers to adopt mechanisms to improve vehicle efficiencies,[4] which should lead to a reduction in fleet-wide energy use. The passenger vehicle sales-weighted emissions targets of 95 gCO_2/km by 2020 are a prominent example of such measures.[5] Its implementation has accelerated emissions reductions from new vehicles with spark-ignition (SI) and compression-ignition (CI) engines.[6] The Central Scenario of the Fifth Carbon Budget of the UK Committee on Climate Change suggests a combination of increasing efficiency of conventional vehicles, switching to novel powertrains (electric vehicles, EV, and plug-in hybrid electric vehicles, PHEV) and fuels (hydrogen) and demand-side reduction could reduce domestic transport emissions to 32 $MtCO_{2e}$ in 2030, with a range of 28−42 $MtCO_{2e}$ for the "Barriers" and "Max" Scenarios, respectively.[7] The extent to which additional efficiency improvements can reduce passenger vehicle emissions to 14.5 $MtCO_{2e}$ (or 14.2 $MtCO_2$) by 2050 remains uncertain, which equates to the sector's 2050 emissions target under an assumption of equitable national reductions.[3]

The uncertain impact of vehicle fleet energy use and emissions has led to recent studies by a number of research groups.[8−12]

Of available vehicle technologies, internal-combustion engine (ICE) vehicles are expected to remain dominant in the fleet for the next 20−25 years.[13−15] A continuous improvement in ICE efficiencies is nonetheless limited by physical design constraints, which includes bounds to engine downsizing and mass reductions. The potential for EV and PHEV to reduce national energy consumption is also largely unknown, as they comprised only 0.02% of the vehicle fleet in 2013.[16] Vehicle stock and energy-demand models are commonly used to deduce such technological potentials.

ICE vehicle design modifications are identified as the best means of reducing UK passenger vehicle emissions in the near-term.[13,15] However, no available transport-fleet models incorporate the effects of deductive, fleet-wide, design changes in estimates of national fuel consumption and CO_2 emissions. The majority of national simulation packages continue to rely on deductive macro-level statistics to develop such valuations (i.e., fleet age, propulsion system substitution,[17−19] vehicle

Received: September 26, 2016
Revised: February 6, 2017
Accepted: February 8, 2017
Published: February 8, 2017

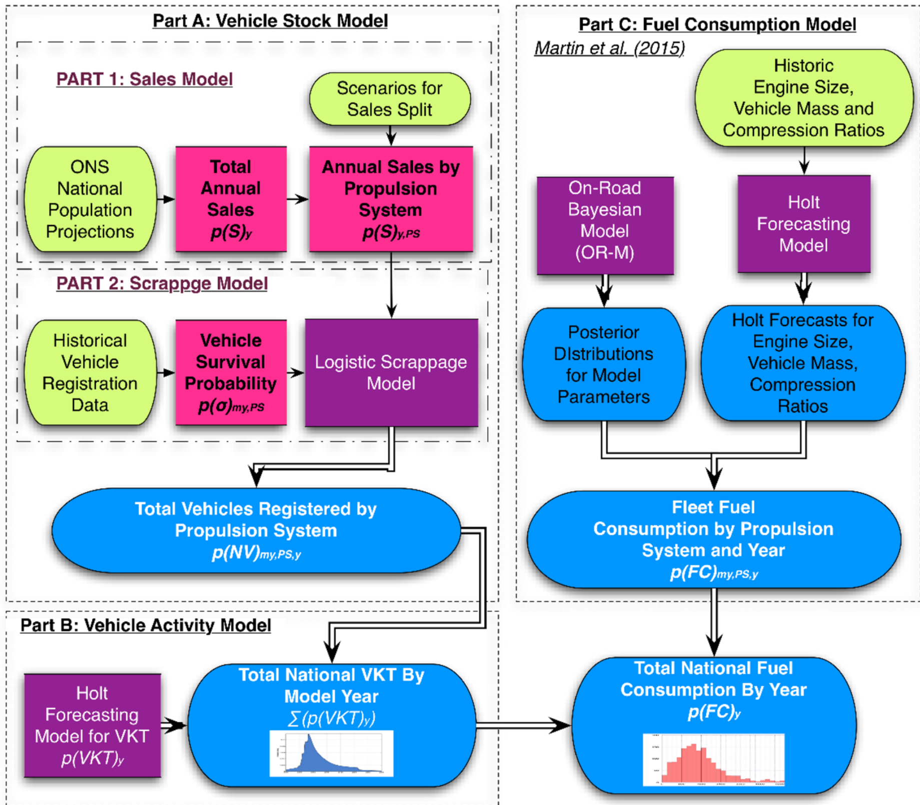


Figure 1. Overview of STEM, which combines the individual (A) vehicle stock, (B) vehicle activity, and (C) CARma fuel consumption models.

design trade-offs,[20−22] distance traveled, etc.).[23−25] Consequently, most models are not able to account for the evolutionary vehicle design developments that have been the primary driver of changes in fleet-wide fuel consumption throughout the last century.

The few approaches that have attempted to account for inductive, physics-based, design variables, such as the ADVISOR[26,27] and Ricardo[28] packages, are similarly noted to undervalue the true diversity of technologies across national fleets. Moreover, extensive and detailed data input requirements, such as engine maps, may limit the practicality of such packages being used to assess fleet-wide effects.[29] In some cases, fleet-wide energy-demand estimates are extrapolated from a small set of representative vehicles: for example, fewer than 10 distinct vehicles have been used to represent the 35 000 unique vehicle-models in the UK.[30] Indeed, a new methodology is required to quantify the influence of evolutionary vehicle design, vehicle mass, engine size, and compression ratio, on national UK fuel consumption and emissions estimates. These three variables are chosen because they account for over 80% of the variance in the rated light duty vehicle (LDV) fleet fuel consumption.[29]

Additionally, existing transport-fleet models cannot represent uncertainties and the influences of modeling assumptions. The National Transport Model,[31] Digest of UK Energy Statistics (DUKES) model,[32] and Energy Consumption UK (ECUK) model[1] estimate different values in passenger vehicle energy use because of uncertainties in their deterministic inputs.[33] Just one transport-fleet model accounts for such variable stochasticity when used to project LDV energy-use and emissions,[34] but is specific to the North American market and incapable of representing structural risk. Therefore, we must account for uncertainties in variables, unknown parameters and modeling inadequacies to better represent inherent modeling risks to those policy makers relying on accurate simulation results for policy development.[25,31,32]

This study demonstrates the impact of ICE vehicle evolution within a fleet to determine the likely trajectory (probabilistic) of national fleet-wide fuel consumption and CO_2 emissions. To do so, a new approach, known as the Stochastic Transport Energy Model (STEM), combines deductive vehicle activity (measured in vehicle kilometres traveled, VKT), scrappage, and sales scenarios with an inductive UK probabilistic fuel consumption model.[29] A data set encompassing all vehicles made available in the UK's fleet since 2001 provides a unique ability to represent detailed vehicle design metrics within a deductive model.[6] The stochastic results provide a more accurate representation of the uncertainty in the underlying assumptions to regulators and policy makers, helping to mitigate risk when developing emissions targets and transport market interventions.

While the proposed methodology allows for the representation of uncertainty within evolutionary parameters, projections for fleet-wide energy-use and emissions were derived under eight distinct scenarios by propulsion system, vehicle model year and calendar year. Vehicle technology improvements were represented by scenarios that account for evolutionary vehicle design changes (Baseline), advanced ICE improvements (High-ICE), high EV adoption (High-EV), and high CI adoption (High-CI). The technology adoption rates under these scenarios are based on expert views expressed in other works which are better suited to scenario development. Therefore, incorporation of exogenous influences, such as energy prices and carbon taxes, and the policies to achieve the scenario outcomes are beyond the scope of this work.

DOI: 10.1021/acs.est.6b04746
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Additional scenarios were considered investigating the influence of falling CO_2 intensity of the national grid (gCO_2/kWh, Decarbonization) and the combination of High-CI and High EV (High CI and EV). Beyond technological transitions, influences of VKT were considered (Constant VKT) to inform policy makers of the effects of targeted vehicle activity policies. Likewise, discrepancies between real-world and standardized New European Driving Cycle (NEDC) fuel consumption estimates were incorporated (On-Road) to quantify differences between the idealized and true national fuel consumption.[24] Combined, the eight scenarios assess the effectiveness of vehicle activity, ICE modification and propulsion system substitution to reduce UK LDV energy use and CO_2 emissions to assess the likelihood of successfully complying with GHG reduction objectives.

METHOD

STEM quantifies national passenger vehicle fuel consumption by combining stock, vehicle activity, and energy-demand estimates, as shown in Figure 1. This paper introduces vehicle stock and VKT activity methodologies which complements the Cambridge Automotive Research Modeling Application (CARma)[29] to project fleet-wide UK LDV fuel consumption.

Stock Model. Similar to other studies,[23,34,35] cumulative LDV sales were assumed to increase linearly with stochastic population projections as simulation time was increased (t, which represents the difference between the calendar year, y, and the initial year of simulation). This ensured consistency for UK vehicle ownership, where vehicle penetrations have remained between 414 and 459 vehicles per thousand people (VPT) since 2000.[16,36] Diffusion of EV and PHEV used the logistic sales function in eq 1,[37,38] which provides the proportion of sales, $p(S)$, as a function of maximum sales by propulsion system (MS_{PS}) specified by scenario. Historical vehicle sales from the UK Department for Transport was used for EV and PHEV growth in Appendix A. The time to maximum sales (MGT_{PS}) and growth rates (GR_{PS}) were similarly determined from statistically significant (p-value $\leq 7.7 \times 10^{-5}$) correlations of historical vehicle licensing data from 2001 to 2013,[16] whose standard errors were incorporated to account for uncertainty.

$$p(S)_{y,\mathrm{PS}} = \frac{\mathrm{MS_{PS}}}{1 + e^{-\mathrm{GR_{PS}}(t - \mathrm{MGT_{PS}})}} \tag{1}$$

The proportion of stochastic spark ignition (SI, $p(S)_{y,\mathrm{SI}}$) and compression ignition (CI) ($p(S)_{y,\mathrm{CI}}$) sales were established by calendar year (y), after EV ($p(S)_{y,\mathrm{EV}}$) and PHEV ($p(S)_{y,\mathrm{PHEV}}$) cumulative sales projections were estimated in eqs 2 and 3.

$$p(S)_{y,\mathrm{CI}} = p(S)_y \cdot [1 - p(S)_{y,\mathrm{EV}} - p(S)_{y,\mathrm{PHEV}}] \cdot R_{\mathrm{ICE},y} \tag{2}$$

$$p(S)_{y,\mathrm{SI}} = p(S)_y \cdot [1 - p(S)_{y,\mathrm{EV}} - p(S)_{y,\mathrm{PHEV}}] \cdot [1 - R_{\mathrm{ICE},y}] \tag{3}$$

The CI to SI sales ratio ($R_{\mathrm{ICE},y}$) was specified by scenario. The vehicle survival probability ($p(\sigma)_{\mathrm{my,PS}}$) was simulated using a S-curve logistic function.[35,39,40]

$$p(\sigma)_{\mathrm{my,PS}} = 1 - \frac{1}{1 + e^{-\mathrm{SP_{PS}}(\mathrm{VA} - \mathrm{MVA_{PS}})}} \tag{4}$$

Median vehicle age (MVA) and survival parameters (SP) were calculated by propulsion system and model year (my) after calibrating to historical vehicle registration data.[16] Survival uncertainties were introduced for the MVA (1.6×10^{-2}) and SP (4.1×10^{-3}) terms using the least-squares standard errors over all data and model years. Vehicles over 33 years of age were indefinitely retained to account for the classic vehicle stock in the simulated fleet. Newer vehicles were quantified by calendar year, model year and propulsion system ($p(\mathrm{NV})_{\mathrm{my,PS},y}$) with the combination of eqs 1 and 4.

$$p(\mathrm{NV})_{\mathrm{my,PS},y} = p(S)_{y,\mathrm{PS}} \cdot p(\sigma)_{\mathrm{my,PS}} \tag{5}$$

Vehicle Activity and Vehicle Fuel Consumption. Holt projections with 95% predictive intervals about mean values were derived for 2030 vehicle activity.[41] Exponentially decreasing functional weights[3] were used to account for annual discontinuities in historical VKT data. Similarly, the Holt functions were used to project CARma inputs to 2030. Mean and standard deviations of SI and CI vehicle mass, engine size and compression ratio were taken from CAP Automotive data.[30] This allowed the stochastic fuel consumption of vehicles to be derived ($p(\mathrm{FC})_{\mathrm{my,PS}}$).

Inputs exceeding plausible design limitations were replaced with maximum values based on physical limitations, such as maximum thermodynamic efficiencies, to maintain credible fleet-wide fuel consumption estimation: (1) The potential for SI and CI vehicle light-weighting is 20–35% based on material substitution and vehicle redesign.[42−46] STEM uses 20% of vehicle mass in 2011 as a conservative, upper limit for light-weighting. (2) The potential for engine downsizing is 20–30%.[47−49] Vehicle performance using a downsized engine is maintained[50] by increasing brake mean effective pressure (BMEP) to counter the reduction in engine displacement. BMEP may be increased through turbocharging/supercharging, layout of bore, stroke and cylinders and improvements to camshaft phasing and direct injection.[51] STEM limits were conservatively set at 20% of 2011 values. (3) Allowable SI and CI compression ratios were bounded within the analysis. SI compression ratios have been increasing in recent years[52] but are expected to reach a maximum of 14 because of preignition issues for higher compression ratios, which one vehicle manufacturer has achieved (Mazda achieves compression ratios of 14 in its SKYACTIVE). New lean burn engine technologies, known as homogeneous charge compression ignition (HCCI), are being investigated and may be able to establish new relationships for engine design and compression ratio. It is expected that these designs will not be a significant part of the fleet before 2025. Conversely, CI vehicles have had their compression ratios decreased over the past decade in order to comply with noxious emissions standards. We do not anticipate that CI vehicles will have lower compression ratios than SI vehicles and thus set a compression ratio floor of 14.[52−54]

Sales-weighted fuel consumption was converted to available-vehicle fuel consumption using an ordinary least-squares statistical regression between both variables. Historic fuel consumption was specified from national Energy Consumption UK data.[2]

National Energy-Use and Emissions. Vehicle stock, activity and fuel consumption estimates were combined in eq 6 to quantify stochastic national energy-use by propulsion system, calendar and model year. Cumulative estimates for energy use (eq 7) and emissions (eq 8) were quantified with a summation over model years and propulsion systems, using conversion factors (CF, MJ/l) and emissions factors (EF, gCO_2/MJ) for gasoline, diesel and electricity generation (see Table 1).

DOI: 10.1021/acs.est.6b04746
Environ. Sci. Technol. 2017, 51, 3093−3101

$$p(\mathrm{FC})_{\mathrm{my,PS},y} = p(\mathrm{NV})_{\mathrm{my,PS},y} \cdot p(\mathrm{VKT})_y \cdot p(\mathrm{FC})_{\mathrm{my,PS}} \quad (6)$$

$$p(\mathrm{energy})_y = \sum_{0}^{\mathrm{my,PS}} (p(\mathrm{FC})_{\mathrm{my,PS},y} \cdot \mathrm{CF}_{\mathrm{fuel}}) \quad (7)$$

$$p(\mathrm{emissions})_y = \sum_{0}^{\mathrm{my,PS}} (p(\mathrm{FC})_{\mathrm{my,PS},y} \cdot \mathrm{EF}_{\mathrm{fuel}}) \quad (8)$$

Table 1. Summary of STEM Model Inputs and Boundary Constraints by Scenario

scenario name	description
baseline	evolutionary VKT, ICE design, and CI sale projections; business as usual EV and PHEV sales
High-CI	baseline values for VKT and ICE design, with a linear 10% annual increase in CI sales to a maximum of 73%[55] in 2020
High-EV	baseline values for VKT, ICE design and CI sales, with high EV and PHEV sales assumptions of 13% and 42%, respectively[56]
decarbonization	High-EV values for VKT, ICE design and sale projections, with national grid decarbonization considered to 2030.[7]
High-CI and -EV	combination of High-CI and High-EV scenarios
High-ICE	identical to baseline, with linear changes in SI and CI engine size, mass, and compression ratio to 2030 technological limits
constant VKT	identical to baseline, with VKT held constant at 2013 average annual vehicle use of 13 380 km[3]
on-road	identical to baseline, with on-road fuel consumption estimates used in lieu of NEDC based values[29]

description	value
average annual population growth, 2013−2030[36]	0.70%/year
proportional baseline EV sales share[56]	3.60%
proportional baseline PHEV sales share[56]	18.20%
proportional High-EV EV sales share[56]	12.70%
proportional High-EV PHEV sales share[56]	41.80%
annual increase in baseline CI sales[16]	2.15%
annual increase in High-CI sales	10.00%
maximum proportional CI sales share[55]	73.10%
PHEV utility factor[57]	65.40%
electricity per mile[57]	5.87 km/kWh
SI vehicle fuel (motor spirit) conversion factor, net	32.75 MJ/l[32]
CI vehicle fuel (diesel engined road vehicle, DERV) conversion factor, net	35.99 MJ/l[32]
SI vehicle CO_2 emissions factor[58]	69.3 gCO_2/MJ
CI vehicle CO_2 emissions factor[58]	74.1 gCO_2/MJ
electricity grid CO_2 emissions factor[59]	487.2 gCO_2/kWh
2030 electricity generation carbon limit[56]	103.87 gCO_2/kWh
grid transmission losses[59]	43.18 gCO_2/kWh
limit of vehicle light-weighting	20% of 2011 mass
limit of engine downsizing	20% of 2011 mass
limit of SI compression ratio	14
limit of CI compression ratio	14

Scenarios and Model Inputs. Two alternative methodologies were adopted for uncertainty estimation. The Bayesian and Frequentist (maximum likelihood estimation) methodologies were used to quantify parametric uncertainty values when sufficient data was available to form statistical correlations (p-value $\leq$ 0.05 and $R^2 \geq$ 0.70) for sales (EV, PHEV, and cumulative), scrappage, evolutionary VKT, and fuel consumption. Scenario-based inputs were adopted in the absence of historical data. This allowed unique combinations of maximum sales rates (EV, PHEV, and CI), constant VKT, grid decarbonization, and vehicle design assumptions to be considered, as defined in Table 1. These bounds of vehicle mass, engine size, and compression ratio were similarly specified by scenario to safeguard against the development of physically unrealistic results.

RESULTS AND DISCUSSION

Historical Stock and Activity Correlations. Vehicle retirement by scrappage is the primary mechanism for fleet turnover, leading to higher fleet-wide fuel efficiency with vehicle improvements. Since 1970, the UK passenger vehicle and scrappage characteristics varied by model year (see eq 4). As depicted in Figure 2, the median vehicle age decreased from

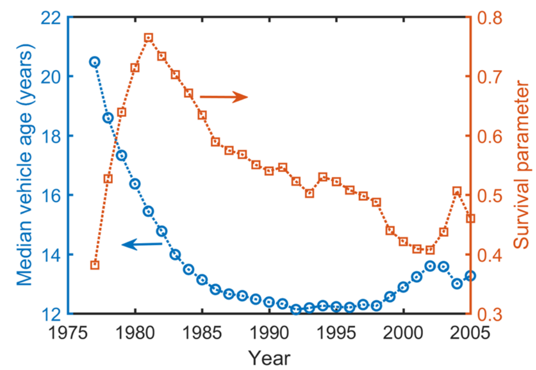

Figure 2. Median vehicle age (MVA) and survival parameters (SP, eq 4) with minimum R^2 = 0.93. Values from 1981 to 2001 have highest statistical significance, with p-values less than 2.2 × 10^{-16}.

1977 to 1992 (21−12 years), remained relatively constant from 1993 to 1998 (mean of 12 years), and increased from 1998 to 2005 (12−13 years). Survival parameters increased from 1977 to 1981 (0.38−0.76), decreased from 1982 to 2002 (0.73−0.41), and increased from 2003 onward (2003 to 0.46 in 2005). The limited availability of vehicle registration data hindered variable estimation from 1977 to 1980 and 2006 to 2013. Therefore, scrappage characteristics are assumed to be relatively constant from 2006 onward in STEM (MVA = 13 years, SP = 0.46), and maximum standard errors were adopted to account for uncertainty (MVA = 1.6 × $^{-2}$ years, SP = 4.1 × 10^{-3}).

The fleet-wide fuel consumption is dependent upon the mix of technologies available from manufacturers and sales volume purchased by consumers. The relationship between the fuel consumption of available vehicles and sales-weighted fuel consumption is described in Appendix F.

The adoption of EV and PHEVs were compared from 2001 to 2013, where it was found that the annual adoption of HEVs and PHEVs since 2004 occurred at a slightly lower rate (201%) to EVs (216%) (see A.1) as determined by fitting logistic functions (eq 1) to historical UK vehicle registration data.[16] This allowed statistically significant regression functions to be derived for both technologies (despite the discontinuities in sales between 2008 and 2010 that are attributed to the economic recession[60]). p-Values of 2.66 × 10^{-11} (EV) and 7.7 × 10^{-5} (PHEV), where a p-value less than 0.005 represents statistical significance, were achieved. The adjusted coefficients of determination (R^2) were accordingly estimated at 0.94 for

DOI: 10.1021/acs.est.6b04746
Environ. Sci. Technol. 2017, 51, 3093−3101

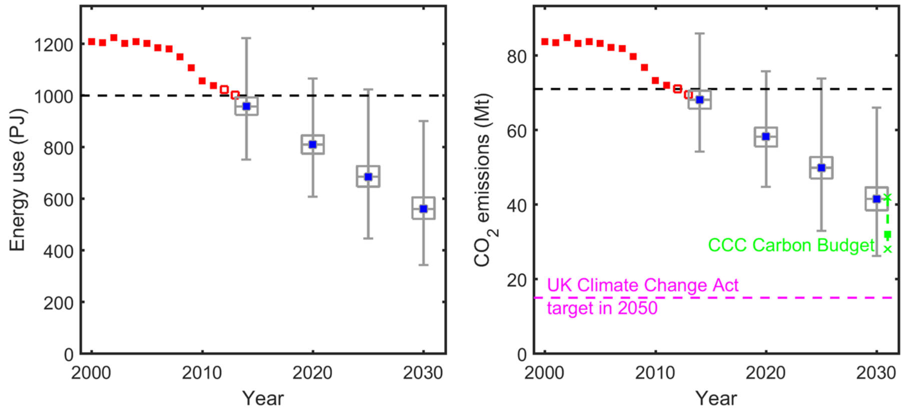

Figure 3. Composite figure of historical (red) and baseline projections (blue) for (a) energy use and (b) CO_2 emissions for UK LDVs. Filled historical data was used in the model. Annual 2012 passenger vehicle energy-use (1000 PJ) and associated CO_2 emissions (71 Mt) represented with black dashed horizontal line. Historical energy use and CO_2 emissions from the UK Department for Transport (DfT) and shifted to account for differences in STEM/DfT methodologies. Total emissions from cars under the Fifth Carbon Budget Central Scenario of 32 $MtCO_2$ in 2030 is given in the green square, with upper and lower crosses denoting the "Barriers" and "Max" scenarios, respectively.[7] The magenta line denotes the fair-sharing limit of 15 $MtCO_2$ based on the UK Climate Change Act[4] fair-sharing target in 2050.

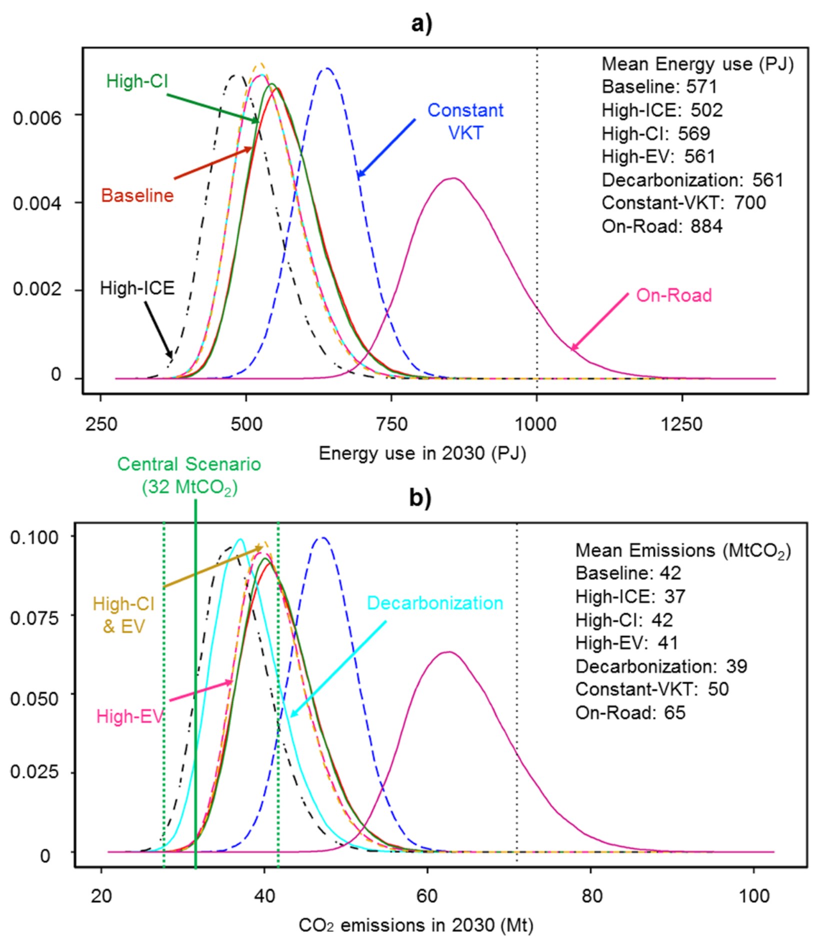

Figure 4. Probability distribution of (a) energy use and (b) CO_2 emissions in 2030 over all propulsion systems, by scenario. Annual 2012 passenger vehicle energy-use (1000 PJ) and associated CO_2 emissions (71 Mt) represented with black dashed vertical line. Vertical green broken lines denote the maximum and minimum CO_2 emissions associated with the Fifth Carbon Budget Barriers and Max scenarios, respectively. The vertical solid green line denotes the Central Scenario estimate of 32 $MtCO_2$.[7] Cumulative value in 2030 shown in E.1.

EVs (p-value = 2.7×10^{-11}) and 0.90 for PHEVs (p-value = 7.7×10^{-5}). Consequently, higher sales of EV, relative to PHEV, influenced STEM propulsion system forecasts, such that maximum EV sales rates were reached nine years ahead of those assumed for PHEVs.

Stock Projections. Proportional sale and stock penetrations were derived by propulsion system using scenario-specific sales estimates (presented in Tables D.1 and D.2). The stock was assumed constant across all scenarios, 30.4 million vehicles by 2030 with a 90% confidence interval between 30.2 and 30.7

DOI: 10.1021/acs.est.6b04746
Environ. Sci. Technol. 2017, 51, 3093−3101

million. This corresponds to likely vehicle penetration levels of 426 VPT, which is within the range of historical values (414–459 VPT).

Since 1994, the UK CI stock has increased by 1.4% per annum.[30] This trend was projected to continue under the Baseline scenario up to a maximum allowable annual share of 73% to match Ireland's CI sales rate in 2012. This rate was second highest in the EU in 2012 (following Luxembourg at 76%),[55] but more closely represents the consumer preferences of the UK population. Despite an assumption that CI sales will increase by 10% per annum under the High-CI scenario, the maximum CI sales rate was achieved just four years earlier in the High-CI over baseline scenario (2020 compared to 2024). This result underscores the UK's high share of CI sales, whose likely penetrations were forecast to increase to 60.6% (90% CI = 60.1–61.1%) and 63.5% (90% CI = 63.0–64.0%) respectively in the 2030 baseline and High-CI scenarios.

Under the High-EV scenario, EV, and PHEV account for 12% and 28%, respectively, of new vehicle sales by 2030 which is only 8.5% and 16% more of the new fleet than in the baseline. The increased sales of electric-based powertrains under this scenario causes the stock of EV to increase from 1.6% in the baseline scenario to 5.6%. Similarly, the PHEV fleet penetration was expected to increase from 6.1% in the baseline scenario to 14%. This emphasizes the prolonged lead times required for new technologies to become incorporated within a national fleet. Thus, electric-based powertrains will have a limited impact on the UK LDV stock by 2030, leaving SI and CI powertrains to comprise more than 60% of the likely fleet in all of the scenarios.

Classic vehicles were projected to account for 4.9% of fleet energy use in 2030, despite constituting only 2.3% of the stock. These technologies are presently exempt from emissions control policies,[61,62] such as MOT tests, the London congestion charge and vehicle excise duty. Thus, there is a contradiction in governmental policies, which support both environmental sustainability and old technologies with their disproportionate environmental impacts.

Baseline Energy-Use and CO_2 Emissions. Holt projections for the mean and standard deviation of SI and CI vehicle mass, engine size and compression ratio (see Figure C.1) were used as inputs to quantify fuel consumption in the CARma model. Mean sales-weighted SI and CI fuel consumption were estimated to decrease from 6.0 L/100 km to 3.9 L/100 km (90% CI = 1.1–8.3 L/100 km) and 5.0 L/100 km to 2.9 L/100 km (0.5–5.3 L/100 km) between 2013 and 2030, equating to annual average improvements of 2.0% (SI) and 2.7% (CI). A comparison to historical average reductions of 2.2% (SI) and 1.9% (CI) between 2001 and 2011[6] indicates the average pace of future reductions will increase. This is a consequence of the Holt model's ability to capture manufacturers' increased emphasis on improving fuel economy after 2007 when mandatory emissions targets were introduced.

The sales-weighted fuel consumption estimates were combined with VKT and stock results to validate the STEM model against official 2012 values and are illustrated in Figure 3. A 2.4% discrepancy exists between the STEM and nationally reported values for passenger vehicle energy-consumption (1001 PJ and 1,024 PJ,[3] respectively) because of differences in their stock methodologies. Similarly, the discrepancy between STEM and DECC CO_2 emissions estimates, of 71 $MtCO_2$ and 64 $MtCO_2$,[3] is attributed to differences in model assumptions: DECC disaggregates emissions factors by vehicle activity and model year (gCO_2/km), while energy-conversion emission factors were used by fuel source in the STEM model (gCO_2/MJ in Table 1). Additionally, DECC results exclude on-road fuel consumption and includes "fuel tourism" effects in its results (i.e., fuel consumption of vehicles purchased abroad), both of which have been previously estimated to increased uncertainty by ±8%.[33]

Baseline annual energy-use and CO_2 emissions were compared to validated 2012 LDV fleet values in Figure 4, from which the likely effects of evolutionary VKT, ICE design, and CI, EV, and PHEV sales trends were assessed. Mean reductions in energy-use and emissions were estimated at 43% (1001 PJ to 571 ± 60 PJ) and 41% (71 $MtCO_2$ to 42 ± 4 $MtCO_2$) between 2012 and 2030, which equated to annual average diminutions of 2.4% and 2.3%. The emissions under the baseline are 31 ± 22% higher than the Fifth Carbon Budget Central Scenario estimate of 32 $MtCO_2$.[7] It was highly probable (99.76% to 99.88%) that the likelihood of evolutionary vehicle technology and activity changes would lead to reductions in national LDV energy-use and emissions. Uncertainties about future projections were quantified with a comparison of the probabilistic energy-use and emissions estimates in 2014 and 2030, whose standard deviations increased by 26% (energy-use) and 30% (emissions).

High-ICE Scenario. The influence of accelerated improvements to SI and CI vehicle mass, engine sizes and compression ratios were investigated in the High-ICE scenario, of which the effects on the UK LDV fleet were greater than any of the other technology-specific scenarios considered. Energy-use and emissions were projected to be between 4% higher and 28% lower than the baseline and between 37% higher and 6% lower than the Fifth Carbon Budget Central Scenario.[7] The likelihood of reductions being achieved was forecast to be 43% using overlapping coefficients between 2014 and 2030 probabilities for both energy-use and emissions.

High-CI Scenario. CI sales had little effect on reducing the environmental impacts of the UK fleet, with energy-use and emissions projected to decline by 0.35% (overlapping coefficient = 98%) and 0.01% (overlapping coefficient = 99%), respectively, over baseline estimates and 31% higher than the Fifth Carbon Budget Central Scenario.[7] The marginal effect of higher CI sales is further emphasized by the observation that CI and SI vehicle efficiency improvements were also considered in this scenario, average available fuel consumption of CI vehicles decrease by 46% between 2011 and 2030 (from 5.5 L/100 km in 2011, to 3.0 L/100 km in 2030[30]), compared to 37% for SI (from 7.1 L/100 km in 2011 to 4.5 L/100 km in 2030[30]). CI sales have increased an average 2.6% annually from 2001 to 2013,[16] at the expense of SI vehicles (−2.8%). Therefore, the existing substitution of SI vehicles limits the extent that increased CI sales can influence emissions going forward. Energy use and emissions fell 2.5% and 1%, respectively, over baseline estimates, when it was assumed CI vehicles comprised all ICE sales by 2020, which confirms the marginal effect of additional CI adoption. Despite the reductions, complete fleet decarbonization is infeasible in both the High-CI and High-ICE scenarios due to their continued dependence on liquid fuels derived from fossil resources.

High-EV, High-CI and -EV, and Decarbonization Scenarios. Under the High-EV scenario, EV and PHEV sales were projected to increase to 12% and 28%, respectively, by 2030. Updated projections suggest uptake of EV and PHEV will account for 60% of new vehicle sales in 2030,[63] compared with

DOI: 10.1021/acs.est.6b04746
Environ. Sci. Technol. 2017, 51, 3093–3101

the 55% estimate used in this work. Other countries and regions, such as Norway and California, show world-leading EV uptake. However, cultural, political, and structural differences make it difficult to transfer those rates to the UK.[64]

This scenario yielded emissions reductions of 1.6% and 1.3%, relative to the baseline and High-CI scenario estimates, respectively, with 94% likelihood of some reduction forecast in both cases. Nonetheless, energy-use and emissions estimates were lower under the High-ICE scenario (502 ± 58 PJ and 37 ± 4 $MtCO_2$) than both the High-EV and High-CI and -EV scenarios (561 ± 57 PJ and 41 ± 4 $MtCO_2$ each) because the long vehicle lifetimes (12 years) slowed fleet turnover and EV adoption by 2030. Under decarbonization, emissions in 2030 are 22 ± 21% higher than in the Fifth Carbon Budget Central Scenario, increasing to 28 ± 21% for both the High-EV and High-CI and -EV scenarios.[7] A probability distribution of energy use and emissions for each scenario is illustrated in Figure 4.

The potential for additional EV sales and emissions reductions was deemed feasible beyond 2030 for two reasons: first, growth in EV and PHEV beyond the modest peak of 5.6% and 14%, respectively, in that year, and second, decarbonization of the national grid in 2012–2030 could yield a 7.4% reduction in emissions (decarbonization scenario).[7] This result provides a viable, yet gradual, alternative to decarbonize the UK's national LDV fleet by coupling grid decarbonization with increased EV adoption to realize the associated environmental benefits.

Constant-VKT Scenario. Holt models forecast continued decline in average (per-vehicle) activity from 13 400 km to 11 600 km (see Appendix B), leading to a 14% decline in mean annual energy-use and emissions by 2030. The absence of such reductions (constant VKT) leads to energy use, which is 23 ± 16% higher than the baseline scenario at 700 ± 56 PJ. Emissions at 50 ± 4 $MtCO_2$ were 19 ± 16% higher than the baseline and 56 ± 20% higher than the Fifth Carbon Budget Central Scenario.[7] Therefore, reductions in vehicle activity are critical in bringing about reductions in overall fuel use and emissions, despite technology changes. Perceived impacts on economic and social health have limited the UK and other countries to focus on vehicle technology improvement for emissions reductions.[65]

On-Road Scenario. Manufacturers' optimization of vehicle performance to the NEDC yielded average fuel economy improvements of 0.17 L/100 km/year for SI vehicles and 0.13 L/100 km/year for CI.[29] The result was growing discrepancy between rated fuel economy and that observed in the real-world. By 2030, this discrepancy was projected to increase by 68% (SI) and 83% (CI). Consequently, forecast mean energy-use and emissions in 2030 were expected to be 55 ± 24% higher than Baseline when CARma on-road factors were used in lieu of NEDC parameter estimates and twice as high as the Fifth Carbon Budget Central Scenario.[7]

The implication is that energy-use and emissions under this scenario are likely to be greater (96.6% and 96.4%, respectively), than baseline estimates.[66] The World-Harmonized Light-Duty Test Procedure (WLTP) is being adopted to overcome the NEDC's shortcomings[67] and an on-road Real Driving Emissions test procedure is also being considered to reduce manufacturers' ability for optimization.[68] However, recent estimates suggest the gap between certified and real-world energy use and emissions using the WLTP could be as high as 31% by 2025.[69] On-road testing using portable emissions measurement systems (PEMS) are being implemented which will likely result in less deviation between rated and on-road performance.

Beyond 2030. As shown, advanced ICE vehicle design changes were the best option to reduce near-term emissions to 2030 since SI and CI technologies were expected to dominate the baseline fleet (92% of vehicles). Combining vehicle lightweighting (−20%), engine downsizing (−20%) and compression ratios of 14 yielded energy use and emissions that were 17% lower than the baseline projection. However, even with concerted effort devoted to ICE technologies our results show that the Fifth Carbon Budget Central Scenario CO_2 emissions reductions are unlikely to be met or exceeded (0.67%). National investment strategies for beyond 2030 should account for both the diminishing likelihood for ICE improvements and potential for higher EV and PHEV sales.

EVs and PHEVs were shown to have a limited ability to reduce CO_2 emissions by 2030. Indeed, the number of vehicles with electric-based powertrains peaked at just 5.6% (EV) and 14% (PHEV) under assumption of the High-EV scenario, resulting in maximum EV-based reductions when paired with grid decarbonization that were 72% likely to achieve reductions relative to the baseline annual emissions. Therefore, manufacturers and legislators should focus on alternative means to maximize national emissions reductions by 2030 and beyond, of which vehicle activity reductions are critical.

To achieve the UK's 2050 Climate Change target, passenger vehicle emissions must fall to 15 $MtCO_2$ (77% reduction from 2012) if the sector is to decarbonize proportionally to all others.[3] The most likely emissions reduction under the baseline scenario is 41 ± 10%, increasing to 45 ± 9% under the decarbonization scenario and 48 ± 10% under the High-ICE scenario. Under the baseline scenario, an additional 39% reduction in emissions is required in the period 2030–2050. The need for emissions reductions from EVs is likely to increase in that period as improvements to ICE diminish. Therefore, proactive adoption of electric-based vehicle technologies is the best strategy for the UK to maximize its chances of achieving the 2050 emissions reductions target.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b04746.

> Further details regarding electric vehicle sales, vehicle activity, vehicle metrics, sales and stock projections, and cumulative energy use and CO_2 emissions (PDF)

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The authors declare no competing financial interest.
Additional data related to this publication is available at the University of Cambridge data repository at https://doi.org/10.17863/CAM.7506.

ACKNOWLEDGMENTS

The authors acknowledge the UK EPSRC funding provided for this work under the Energy Efficient Cities Initiative (EP/

F034350/1) and the Centre for Sustainable Road Freight Transport (EP/K00915X/1).

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